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On the stability of 3D exoplanetary systems

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Abstract

To date, more than 600 multiple planet systems have been discovered. Due to the limitations of the detection methods, our knowledge of the extrasolar systems is usually far from complete. In particular, for planetary systems discovered with the radial velocity technique, the inclinations of the orbital planes (and thus their mutual inclination and the planetary masses) are unknown. Our work aims to constrain the observations of several non-resonant two-planet extrasolar systems. Through analytical analysis based on a first-order secular Hamiltonian expansion and numerical explorations performed with a chaos detector, we identify ranges of values for the mutual inclinations which ensure the long-term stability of the detected systems. Particular attention is also given to determine the possibility for the planetary systems to be in a Lidov-Kozai resonant state.

1 Introduction

For two-planet systems detected with the radial velocity method, no information can currently be derived on the mutual inclination between the two orbital planes. For highly inclined systems, Lidov-Kozai resonance ([6, 2]) offers a secular phase-protection mechanism, ensuring the long-term stability of the systems. In particular, [4] have shown that several extrasolar systems have orbital parameters compatible with a Lidov-Kozai resonant state at high mutual inclination. Here, we aim to pursue this study by investigating the spatial architecture of 16 detected planetary systems, focusing in particular on the extent of the resonant region and its consequences on the system stability.

2 Analytical model

We consider the three-body problem of two planets revolving around a central star. To reduce the number of parameters to be considered (each planet has 6 orbital elements), we adopt an analytical approach which allows to reduce the problem to two degrees of freedom. To do so, we refer the orbits to the invariant Laplace plane (as a result of the conservation of the total angular momentum **C**). Following [5], we expand the Hamiltonian in planar Poincaré variables $(\boldsymbol{\Lambda}, \boldsymbol{\lambda}, \boldsymbol{\xi}, \boldsymbol{\eta})$ and in the parameter $D_2 = ((\Lambda_1 + \Lambda_2)^2 - C^2)/\Lambda_1\Lambda_2$ (as defined in [7]). Being interested in the secular evolution of the system, we average over the fast angles, obtaining the following two degrees of freedom formulation

$$H(D_2, \boldsymbol{\xi}, \boldsymbol{\eta}) = \sum_{j=0}^{ORDECC/2} C_{j,\boldsymbol{m},\boldsymbol{n}} D_2^j \sum_{|\boldsymbol{m}|+|\boldsymbol{n}|=0}^{ORDECC-j} \boldsymbol{\xi}^{\boldsymbol{m}} \boldsymbol{\eta}^{\boldsymbol{n}},$$

where *ORDECC* is the maximal order in the eccentricities (here fixed at 12). As shown in previous works (see for instance [3]), if the system is far from a mean-motion resonance, this secular approximation at first order in the masses is accurate enough to describe its evolution. Moreover, for most of the systems, we show that this expansion is valid up to very high values of the mutual inclination ($i_{mut} \simeq 80°$).

3. Parametric study and results

We study the spatial resolution of several extrasolar systems (HD 11506, HD 117618, HD 12661, HD 134987, HD 142, HD 154857, HD 1605, HD 163607, HD 164922, HD 169830, HD 177830, HD 207832, HD 37605, HD 4732, HD 74156 and HD 85390), by varying the mutual inclination i_{mut} and the inclination of the orbital planes. We choose to vary both orbital plane inclinations in the same way (parameter i), to keep the mass ratio constant. The other orbital elements of the systems are taken from the online database `exoplanets.eu`.

For each system, we provide ranges of values of i_{mut} and i which ensure the long-term stability of the system. On the one hand, we identify precisely the extent of the Lidov-Kozai region characterised by the libration of the argument of the pericenter of the inner planet ω_1. On the other hand, regular 3D planetary configurations are revealed by means of the MEGNO chaos indicator [1]. An example is shown in Fig. 1 for HD 11506.

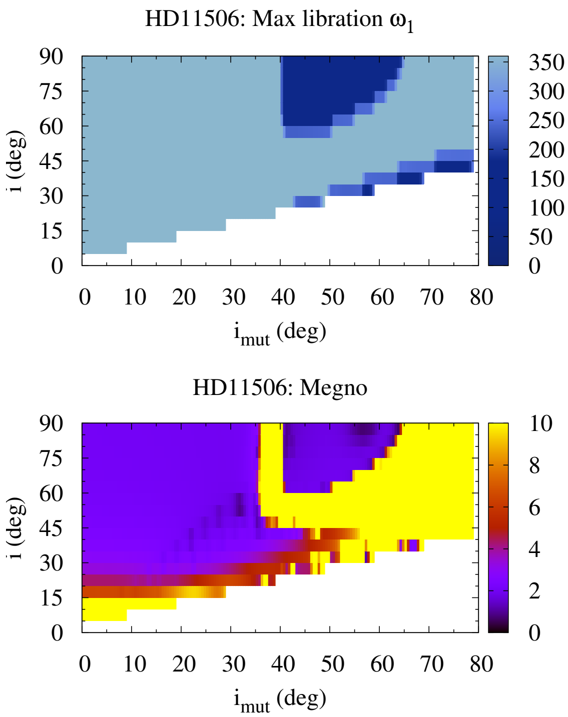

Figure 1: Parametric study of the system HD 11506. Top panel: maximal libration of ω_1. Bottom panel: MEGNO values.

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